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GPS based surface displacements – a proxy for discharge and sediment transport from the Greenland Ice Sheet

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Abstract

The elastic response of the Earth's surface to mass changes has been measured with Global Positioning System (GPS). Mass loss as accumulated runoff and sediment transport from a 10 000 km² segment of the Greenland Ice Sheet (GrIS) correlated very well ($R^2 = 0.83$) with GPS measured uplift. Accumulated winter precipitation correlated fairly well with surface depression ($R^2 = 0.69$). The relationships are based on seven years of runoff and sediment transport observations from the Watson River (2007–2013), winter precipitation from Kangerlussuaq Airport and GPS observations at Kellyville. GPS recordings of surface subsidence and uplift from 1996–2013 are used to calculate 18 years time series of annual runoff, sediment and solute transport and winter precipitation. Runoff and related transport of sediment and solutes increase over the period, while winter precipitation (land depression) tends to decrease. Based on the entire GPS record (1996–2013), it is shown that until 2005–2006 the mass balance of this segment of the GrIS was rather stable – since then there has been an increasing loss of mass, culminating in 2012.

1 Introduction

This study focuses on vertical and horizontal surface displacements due to mass loss from the Greenland Ice Sheet (GrIS) at the GPS station located at Kellyville (KELY). KELY (longitude = 50.9448° W, latitude = 66.9874° N) has been operating continuously since 1996 (Wahr et al., 2001; Khan et al., 2008) and detect a fairly regular pattern of annual depression with a maximum in April–July and uplift of the land surface with a maximum in October–January, which however is showing an increasing accumulated uplift recently. This pattern could be interpreted as an elastic response to the weight of accumulated snow during the winter and loss by runoff caused by melting during the summer.

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Discharge and sediment transport have been measured in Watson River, draining a 10 200 km² catchment, whereof 94 % is covered by a segment of the GrIS, Hasholt et al. (2013). Meteorological observations covering the period have been carried out at Kangerlussuaq Airport by the Danish Meteorological Institute (DMI). The GPS station at Kellyville, is located close to the outlet from Watson River.

Because of this favourable combination of data, it was decided to test if the recorded surface changes could be related to the recorded mass changes. The aim of this presentation is to investigate the possible correlation, and if found significant, to use the relationships to calculate previous runoff and sediment and solute transport, 1996–2006.

2 Study area

The 10 200 km² catchment including the large segment of the GrIS is located in West Greenland, see Fig. 1. There is no calving from this catchment which is drained by the Watson River, which has its outlet into the Kangerlussuaq (Søndre Strømfjord) just south of Kellyville, see Fig. 1. The catchment stretches all the way to the drainage divide between the east and the west coast of Greenland. The divides against neighbouring segments of the GrIS are determined by surface topography. The margin of GrIS is located 30 to 50 km east of the gauging stations, see Fig. 1. The catchment consists mainly of gneiss and amphibolites from the Naqssuqtoqidian orogeny, Henriksen (2005).

3 Methodology

The present-day unloading of ice causes the Earth to respond elastically (Farrell, 1972), resulting in both vertical and horizontal elastic surface displacement of the crust (Dietrich et al., 2005; Jiang et al., 2010; King et al., 2012; Bevis et al., 2012; Fu et al., 2013; Wahr et al., 2013; Yang et al., 2013; Khan et al., 2014; Groh et al., 2014).

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The magnitude of the displacement is proportional to the mass of the load and inversely proportional to the distance between the load and the observing point (Nielsen, 2012). If a load is removed, the observing point uplifts and moves away from the load (Wahr, 2013). The present-day unloading along the margin of the GrlS is detectable using GPS observations (Khan et al., 2010; Bevis et al., 2012; Nielsen et al., 2013).

To estimate site coordinates from GPS measurements, we follow the procedure of Khan et al. (2010). Data is sampled every 30 s, however, there are few gaps; sometimes up to three months of observations are missing. Within the test period values are missing in 2009 and 2010, however, the missing values do not have any influence of the calculated depression and uplift for the two years.

Discharge is measured at the bridges just south of the airport, Fig. 1. Stage is recorded by pressure transducers located upstream the bridges. Discharge is measured by use of the velocity \times area method at the bridges and a rating curve is established in order to calculate the discharge continuously, the estimated accuracy of the accumulated annual discharge is -15% to $+45\%$ for the study period. The upper uncertainty of $+45\%$ is including the possible systematic error caused by using the deepest possible cross section in all the discharge calculations (see Hasholt et al., 2013 for details).

Precipitation is recorded by DMI with a Hellman rain gage at the airport, Fig. 1. Winter precipitation falls as snow (October–April) and summer precipitation is often convective. Here we use uncorrected precipitation as an indicator of the winter precipitation, being aware that it probably underestimates the precipitation significantly (Allerup et al., 2000).

Annual uplift is determined by subtracting the annual (calendar year) minimum surface elevation from the annual maximum elevation. Annual depression is determined by subtracting maximum surface level from the previous year from minimum surface of the calendar year. Because this is a difference measure, the accuracy of each surface observation of $\pm 0.8\text{--}2\text{ mm}$, will cause higher uncertainties at the low uplift and depression values than at the high ones. Average “error” was 1 mm, implicating that a surface

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change of 6 mm (minimum recorded) has an uncertainty of $\pm 33\%$ while a change of 23 mm (maximum recorded) has an uncertainty of $\pm 10\%$.

The correlation between accumulated discharge and sediment transport and uplift is shown in Figs. 2 and 3. Related statistics is shown in Table 1. It is seen that the correlation is highly significant and the relationship can therefore be used to calculate previous discharge and sediment transport. The correlation between accumulated winter precipitation and surface depression is shown in Fig. 4. The correlation is lower, but significant. It confirms that surface depression is related to deposition of snow, but a calculation of winter precipitation using this relationship is less accurate.

4 Results

The entire GPS record is shown in Fig. 5. It is observed that the record is nearly horizontal until 2005–2006, thereafter the record moves upward indicating an increased uplift. The horizontal surface displacement for the entire period is shown in Fig. 6. It is observed that there is a displacement towards west and north, also starting around 2004–2006. Annual uplift, depression and uplift minus depression from the preceding winter are plotted in Figs. 7, 8 and 9. It is seen that the uplift has an increasing trend over the period while the depression has a decreasing trend. The net effect, Fig. 9, indicate an increasing mass loss during the 17 year period.

The calculated annual accumulated discharge and sediment transport is shown in Figs. 10 and 11. Averages of discharge, sediment transport, transport of solutes and winter precipitation over the entire period are shown in Table 2.

5 Discussion

Figure 6 shows relative horizontal displacements. In general, horizontal displacements are dominated by tectonic plate motions. To overcome this problem, we remove the 1996–2004 trend and study changes in horizontal displacements rather than absolute

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displacement. The horizontal displacements after 2004, suggest surface motion away from the Watson River drainage, confirming that the observed uplift at KELY is due to mass loss centred at the Watson River drainage. The correlation functions between accumulated precipitation and discharge and respectively depression and uplift can be described as linear as expected because of the elastic response of the surface upon the weight changes. Slightly better R^2 values can be obtained when using exponential or power functions, however, they are not significantly different from the R^2 values for the linear functions, and therefore we use the simple linear functions. The good correlation between uplift and sediment transport could be expected because the sediment transport is well correlated to the discharge, $R^2 = 0.95$. Also the solute transport is strongly correlated to the discharge. Because of the good correlation with discharge at this location, it is reasonable to calculate sediment and solute transport from the GPS record, although it should be kept in mind that the weight component of these two transport forms is less than 2 per mille of the weight of the accumulated discharge. It is observed that the trend lines are not passing through the origo. When the depression or the uplift is zero, then the winter precipitation and the discharge are negative. This indicates that the measured mass changes do not include all mass changes. The winter precipitation used is uncorrected and from a dry area, it is therefore too low. The total mass loss during the melt season includes the measured runoff and an unmeasured evapotranspiration which may explain part of the deviation from origo. A possible underestimation of the discharge will have the same effect. The actual evaporation and sublimation may add to the uncertainty of the actual mass loss that is to be compared with the GPS “balance” reading. An important point is that in this catchment, there is no mass loss because of calving, which could elsewhere blur the response because of the released melt water alone, this implicate a possibility for calculating calving indirectly by use of the GPS readings elsewhere if the melt loss is known. The calculated “winter precipitation” represents only the uncorrected precipitation at Kangerlussuaq, a point value that has to be calibrated before being used in mass balance studies. The

runoff instead represents the average loss from the ablation area, which is important for evaluation of real mass balance changes.

6 Conclusions

GPS recorded land surface changes can be used as a proxy for calculating winter precipitation and accumulated seasonal discharge from the proglacial Watson River, and in the present case also to calculate the sediment and solute transport.

GPS recordings give valuable information about net mass balance changes of this segment of the GrIS.

The mass balance of this segment of the GrIS has been quite stable until 2005–2006 and thereafter there has been an increasing net mass loss, culminating in 2012.

The analysis described here demonstrates that GPS and discharge provide complementary constraints on the present-day mass imbalance of the Greenland ice sheet. This approach could be useful as long time spans of data become available from the ~ 60 permanent GPS stations deployed around the edge of the ice sheet as part of the Greenland GPS Network (GNET) (Bevis et al., 2012).

Acknowledgements. Support is received from the Commission for Scientific Research in Greenland and from the Danish Natural Science Research Council. The Watson River discharge data collection was supported by the Danish International Polar Year programme, the Greenland Analogue Project (GAP) and the SEDIBUD Project. Technical and logistic support is provided from Center for Permafrost (CENPERM), DNRF no. 100. Gratitude also goes to the NEEM project for facilitating logistic support in Kangerlussuaq. S. A. Khan was supported by the Danish Research Council (FNU).

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Table 1. Correlation statistics.

	<i>n</i>	Average	R^2	<i>p</i>	Std. error estimate
Acc. discharge vs. uplift (km ³)	7	3.9	0.83	< 0.005	0.6
Sed. trans vs. uplift (mio. ton.)	7	8.8	0.83	< 0.005	1.6
Winter precip vs. depres. (mm)	7	59	0.68	< 0.025	6

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Table 2. Average of runoff, sediment transport, solute transport and winter precipitation.

	<i>n</i> years	Average	Maximum	Year	Minimum	Year
Acc. discharge (km ³)	18	3.9	6.2	2012	1.3	1997
Sed. trans. (mio. ton.)	18	6	16.4	2012	0.2	1997
Sol. trans. (mio. ton.)	18	0.028	0.056	2012	0.012	1997
Winter prcp. (mm)	17	69	104	2000	37	2006

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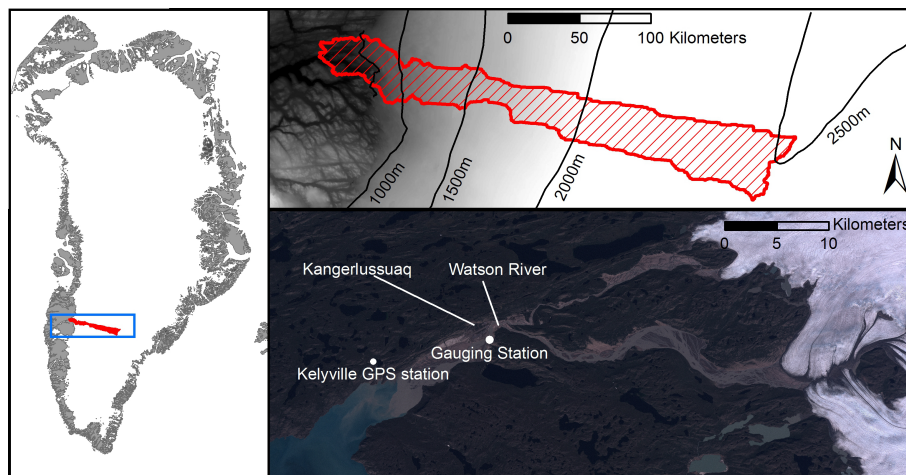


Figure 1. Left: the study area location. Top right: the catchment shown on top of a digital elevation model. Bottom right: a zoom in on the proglacial part of the study area. The background is a Landsat satellite image.

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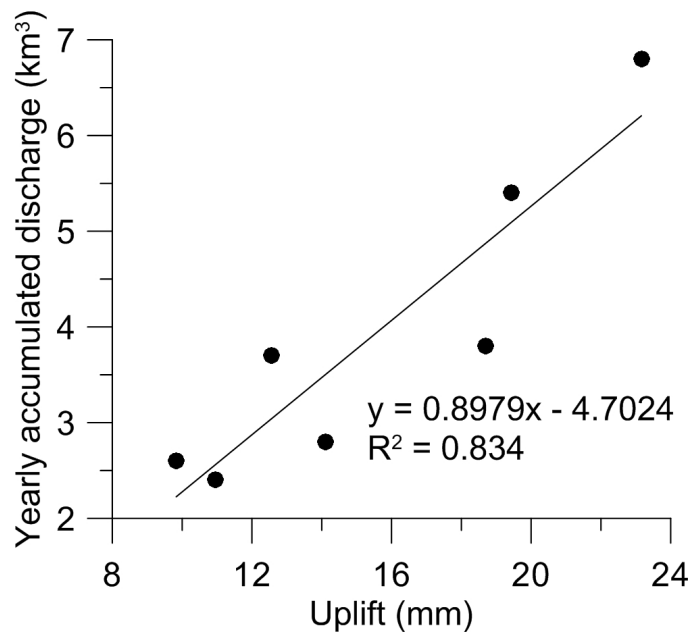


Figure 2. Correlation between surface uplift and yearly accumulated discharge.

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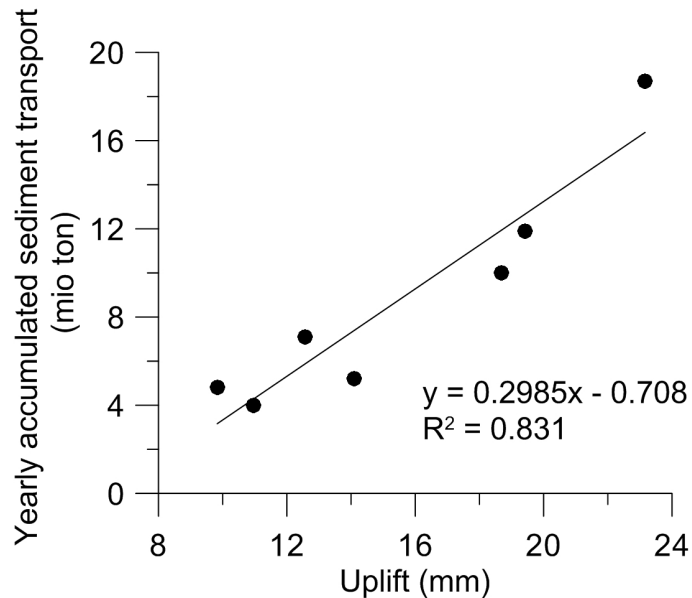


Figure 3. Correlation between surface uplift and yearly sediment transport.

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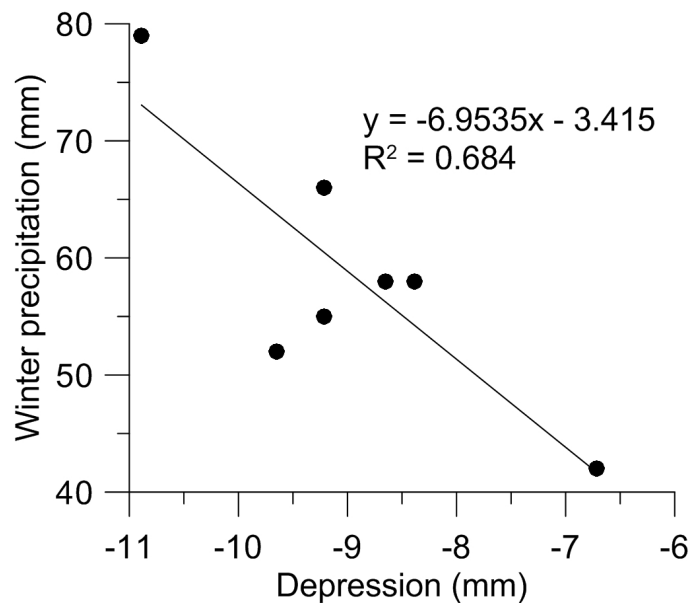


Figure 4. Correlation between surface depression and accumulated winter precipitation.

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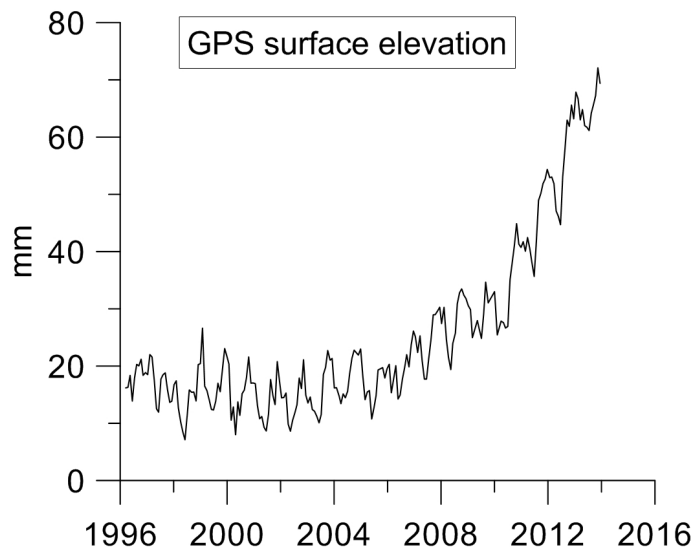


Figure 5. GPS surface elevation 1996 to 2013.

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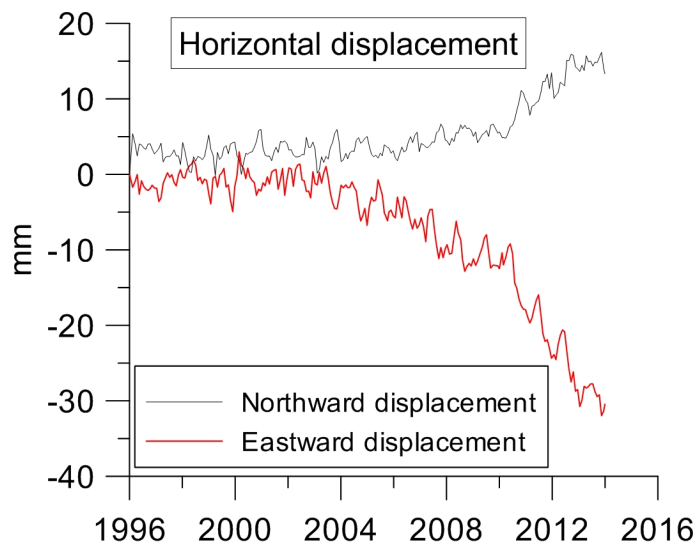
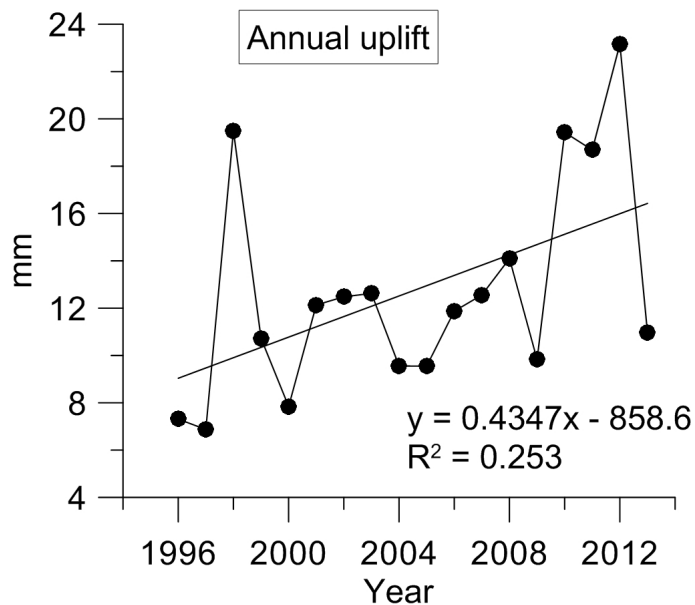


Figure 6. GPS horizontal surface displacement.

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**Figure 7.** Annual surface uplift 1996 to 2013.

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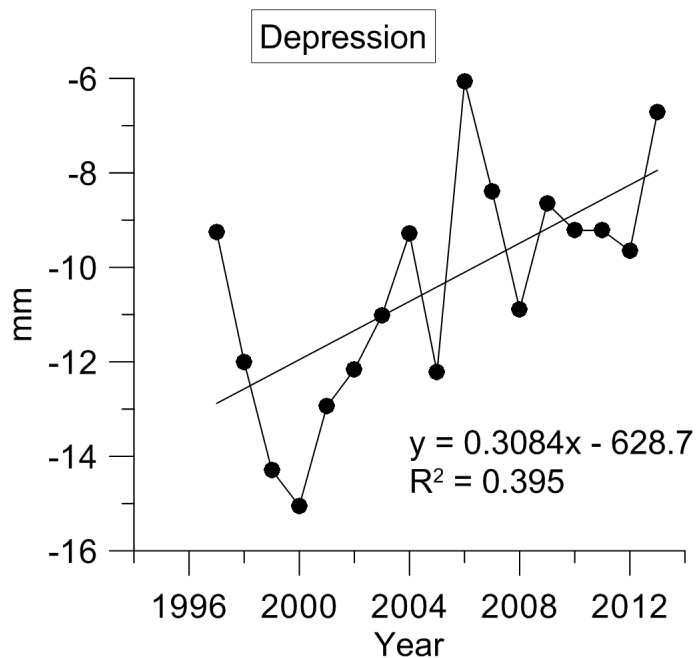


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**Figure 8.** Annual surface depression 1997 to 2013.

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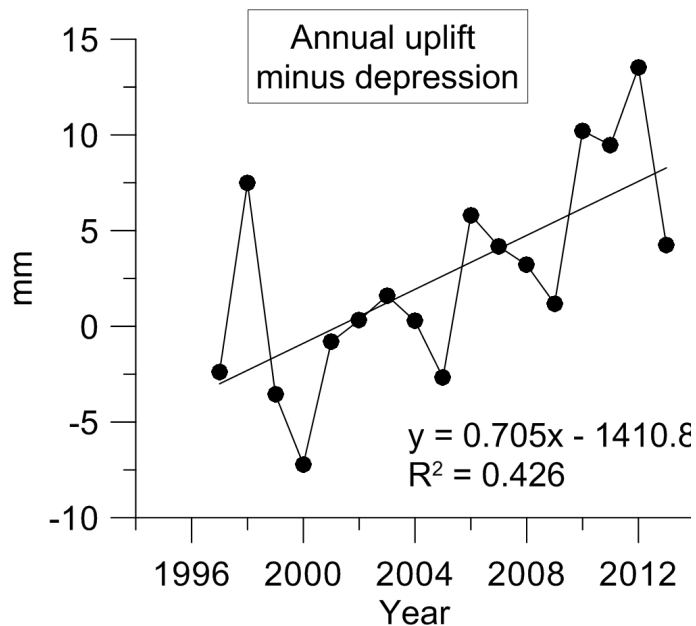
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**Figure 9.** Annual uplift minus preceding winter depression.

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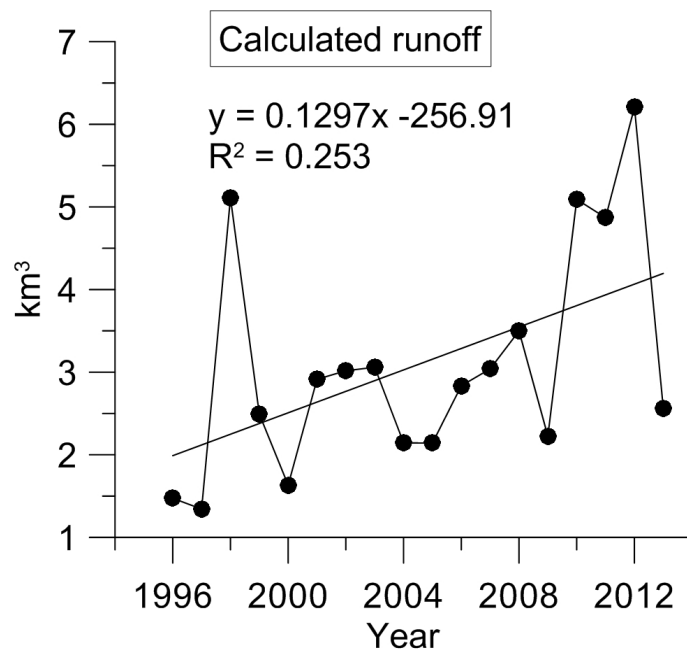
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**Figure 10.** Annual accumulated discharge (runoff), km³, 1996 to 2013.

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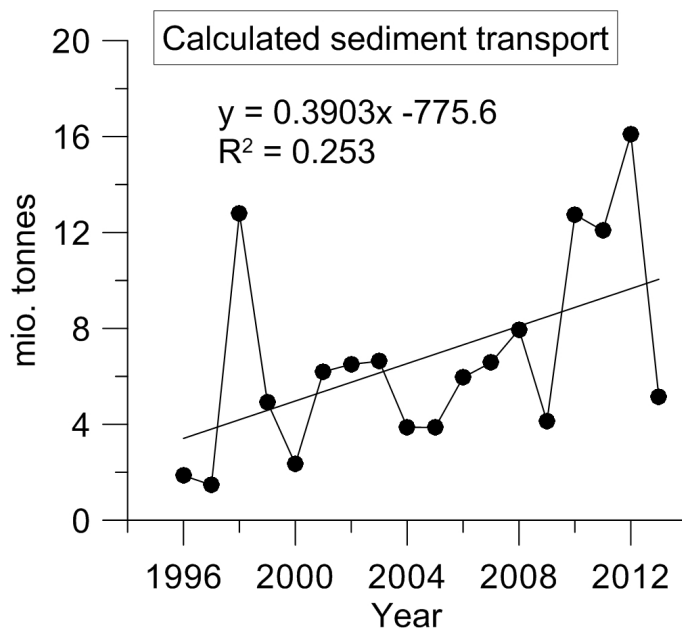
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**Figure 11.** Annual sediment transport (mio. tonnes) 1996 to 2013.

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